SIMULTANEOUS MONITORING OF STORED GRAIN WITH RELATIVE HUMIDITY, TEMPERATURE, AND CARBON DIOXIDE SENSORS

H. B. Gonzales, P. R. Armstrong, R. G. Maghirang

ABSTRACT. *Grain moisture content (MC) and temperature (T) are the primary factors affecting grain deterioration in storage. If these factors are not properly monitored and controlled, grain quality can deteriorate quickly due to mold growth and insect infestation. This research examined use of relative humidity (RH), T, and carbon dioxide (CO_2) sensors for their suitability to determine adverse storage conditions of wheat. A mock-up storage system was constructed and used to simulate a wheat storage bin 6.86 m high. Sensors for T, RH, and CO_2 measurement were placed at various depths in the storage. High-moisture grain, comprising about 11% of the grain volume, was placed in the top section of the bin. Wheat was aerated with the high-moisture grain conditioned to nominal MCs of 14%, 16%, and 18% wet basis (MC_{wb}) and the remaining grain at approximately 11% MC_{wb}. Sensors monitored air conditions during the entire storage period. Aeration was provided over 3-h periods at rates of 0.083 m^3/min/tonne (eight experiments) and 0.166 m^3/min/tonne (one experiment). Airflow was from top to bottom of the bin. CO_2 sensors were effective in indirectly detecting moist grain conditions due to the large amount of CO_2 generated from the wet grain. CO_2 measurement was less effective as grain temperature was reduced as a result of aeration. CO_2 levels monitored at the exhaust of the aeration duct were generally adequate in determining adverse storage conditions. The equilibrium moisture content (EMC) of wheat, determined from RH and T, gave reasonably accurate measurements of grain MC. EMC measurements were also effective in determining moisture changes in the grain due to the moisture front movement from the high-moisture grain.*

Keywords. *Carbon dioxide, Equilibrium moisture content, Grain storage monitoring, Sensors.*

Moisture content (MC) and temperature (T) are primary factors affecting stored grain conditions. High MC in grain can occur due to improper moisture monitoring of grain during harvest, moisture migration caused by in-storage air convection currents, moisture diffusion within bulk seed, or entry of water into the storage bin (White et al., 1982; Khankari et al., 1994; Noyes and Navarro, 2002). High T in grain and spontaneous heating are caused primarily by the heat of metabolism of growing molds when stored grain contains excessive moisture (Zeleny, 1954; Noyes and Navarro, 2002). Seasonal changes in air T and solar radiation create T gradients in the stored grain. These gradients cause air convection currents, which in turn cause moisture to migrate from warm to cool regions of the grain bulk. To eliminate or minimize moisture migration, grain T should be equalized by aeration. Aeration can also cool the bulk-stored grain to a level where growth of molds and insects will be slowed or stopped (Christensen and Kaufman, 1969). Monitoring and control of T and MC are thus important for safe grain storage.

Temperature monitoring has been the traditional method for detecting heated grain but has limitations due to low thermal diffusivity of the grain (Singh et al., 1983). Temperature monitoring systems typically consist of thermocouples attached to structural cables that extend from the top to bottom of grain storage bins. Previous research has examined T and RH sensor modules to measure air conditions (Plummer et al., 1989) and for moisture measurement of rice and dent corn (Chen, 2001). Uddin et al. (2005) studied the accuracy of grain MC prediction using T and RH sensors.

In addition to MC and T, CO_2 evolution has also been identified as a measure of grain deterioration (Saul and Steele, 1966; Steele, 1967; Steele et al., 1969). High levels of CO_2 have been shown to be related to the presence of respiring microorganisms and grain dry matter loss (DML). These studies investigated effects of T and kernel mechanical damage (MD) on the rate of deterioration of shelled corn and effects of MC, T, and MD on deterioration of shelled corn as determined by CO_2 production. Research by others has also demonstrated that MD affects storability of grain and that allowable storage time of grain decreases with higher levels of MD (Wilcke et al., 1993; Ng et al., 1995; Ng et al., 1998;

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Al-Yahya, 1999). White et al. (1982) examined spoilage of stored wheat in relation to intergranular CO_2. They related cumulative values of CO_2 output to wheat conditions during storage. Wilcke et al. (1999) examined the effect of scab (*Fusarium* head blight) on storability of three varieties of hard red spring wheat (*Triticum aestivum*). They used CO_2 evolution to determine DML during storage at 16%, 18%, and 20% MC_{wb} and 20°C. Recent researchers have used gas-specific CO_2 sensors (Maier et al., 2002; Ileleji et al., 2005) to monitor CO_2 production from stored grain and related increased CO_2 levels to early spoilage detection. Unlike T and RH sensors, CO_2 sensors are not at a similar level of miniaturization and development, and are considered most suitable to monitor storage headspace and aeration exhaust ducts.

No research has been published on use of RH, T, and CO_2 sensors for simultaneous monitoring of stored grain. Thus, it would be beneficial to determine the effectiveness of these sensors to provide more timely and reliable detection of adverse grain storage conditions.

The objective of this research was to examine the effectiveness of storage parameters (RH, T, and CO_2 concentration) in identifying adverse storage conditions caused by a small mass of wet grain within the grain bulk during aeration of wheat. Also examined is the location of the sensors in relation to their effectiveness.

Materials and Methods

All experiments were conducted at the Engineering Research Unit of the USDA-ARS Grain Marketing and Production Research Center, Manhattan, Kansas. A mock-up storage system was constructed to simulate an aerated storage bin. The storage bin was located inside a thermally controlled environmental chamber and supplied with aeration conditioned to specific temperature and humidity conditions.

Figure 1 shows the schematic diagram of the mock-up storage system consisting of 0.20-m-diameter and 0.64-cm-thick PVC columns, connected in series with 2.54-cm-diameter plastic hose clamped to an adapter fixed to the column cap. Height of the first column was 0.76 m, while height of each of the other four columns was approximately 1.52 m for a total simulated bin depth of 6.86 m. The bottom part of each column was capped and sealed to prevent air leakage during aeration. A perforated metal grate was affixed 5 cm above the bottom of each column to support the grain mass. A 2.7-hp, rotary-valve air pump (Link Belt, Lexington, Ky.) connected to the 0.76-m column supplied the aeration air. The air supplied by the pump was conditioned to specific RH and T parameters 1 h prior to each aeration period using an Aminco Aire unit (Model 4-5460A, American Instrument Company, Silver Spring, Md.). Airflow rate was measured with a rotameter (FL-806 Omega, Stamford, Conn.).

Six, non-dispersive infrared CO_2 sensors (Ventostat 8102, Telaire, Goleta, Calif.) were used to measure CO_2 concentration. This type of sensor was similar to the CO_2 sensor used by Ileleji et al. (2005). One sensor was fixed on the cap covering the top of each column of grain. A sensor was also placed in an exhaust box to eliminate dilution of the aeration CO_2 with the chamber air. The CO_2 sensor had a voltage output (0 to 10 volts) and ppm readout (0 to 10000 ppm).

RH and T of the grain were measured at locations shown in figure 1 using a SHT75 single-chip RH and T multi-sensor module (Sensirion AG, Zurich, Switzerland) and was the same model used by Uddin et al. (2005). Sensor data was used to determine the equilibrium moisture content (EMC) of the grain and is herein referred to as the EMC sensor. Sensors were protected from grain dust and other contaminants by enclosing each inside a porous polymer tube (X-5108-60µ 1/8” Tube HDPE, Porex Corp., Fairburn, Ga.). One EMC sensor was placed just below the surface of the grain mass in the 0.76-m column; this location was designated as 0 m. Two sensors, fixed to a wooden stick and spaced 0.76 m apart, were placed inside each of the four 1.52-m columns. One EMC sensor was placed at the air inlet in the 0.76-m column.

The CO_2 and EMC sensors were connected to data acquisition boards (PMD-1208LS and PCI-DAS 1000, Measurement Computing Corp., Norton, Mass.) installed in a computer. Rate of individual CO_2 sensor readings was 12 measurements per minute; EMC sensor measurement rate was 2 readings per minute.

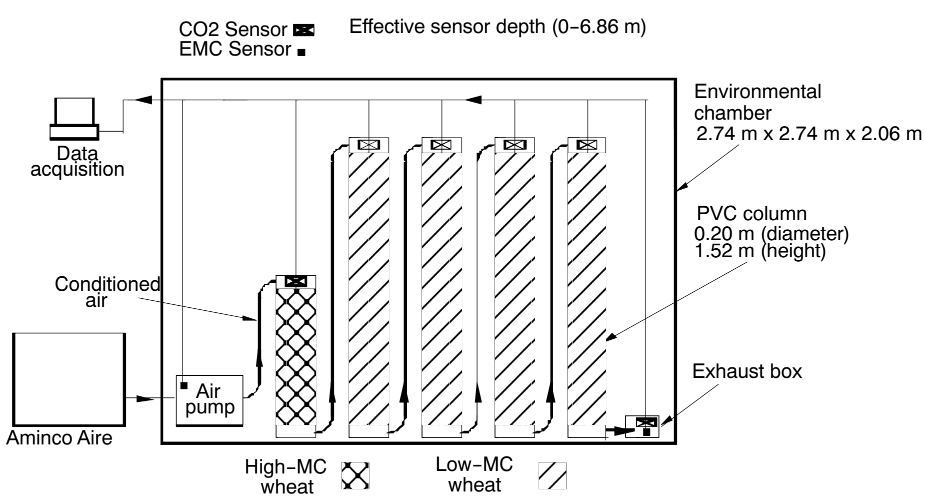

Figure 1. Schematic diagram of the experimental apparatus simulating a storage bin 6.86 m in height (not drawn to scale).

Commercial hard red winter wheat was used in all experiments. Initial MC_{wb} of the wheat was approximately 10.3%, which was determined by oven-drying (*ASABE Standards,* 2005b). All four 1.52-m columns were filled with this dry wheat which comprised 89% of the total bin volume. The first column was filled with high-moisture wheat and comprised 11% of the total bin volume. High MC wheat was prepared by adding distilled water (dH_2O) and gradually mixing in a mixer (Model OS, Mac Lellan Batch Mixer, Anglo American Mill Corp. Inc., Owensboro, Ky.). The nominal MCs of the high-MC wheat were 14%, 16%, and 18% MC_{wb}. After mixing, the high-MC wheat was put inside buckets, sealed, and allowed to equilibrate for 5 days inside a cooler at 5°C.

Experimental Procedure

Table 1 shows actual MC of the high-MC wheat and the sequence of experiments in this study. MC values were determined from the average of three replicates by oven-drying (*ASABE Standards,* 2005a). Aeration was done at an airflow rate of 0.083 m^3/min/tonne or 0.166 m^3/min/tonne for 3 hours every 24 h and for 8 days equivalent to 8 runs for each experiment. An airflow rate of 0.083 m^3/min/tonne is typical for wheat aeration and the 3-h aeration period used is typical of the period of time ambient conditions would allow commercial aeration to occur.

The environmental chamber T was set 1 h prior to each aeration period. For experiments 2 to 9, chamber T was decreased on day 5 and again on day 7 to simulate a wider range of aeration T conditions compared to experiment 1. Average grain T after the fourth aeration period of experiment 1 was observed to have approached the chamber T, leading to the decision of decreasing aeration T for period 5 and again for period 7 for subsequent experiments. Mean aeration RH and T sensor readings with calculated EMC values are listed in table 2. The initial grain T of approximately 29.4°C, simulating grain harvest T, was attained by setting the environmental chamber to this T prior to the first aeration period for 24 h.

The modified Chung-Pfost equation was used to calculate the EMC using constants of A = 610.34, B = 0.15526, and C = 93.213 for hard red winter wheat (*ASABE Standards,* 2005b). The EMC_{db} obtained from the equation was converted to wet basis MC.

Table 1. Experimental sequence for simulated aeration.

Experiment No.	Initial MC of Wet Grain[a], %wb	Airflow Rate, m^3/min/tonne
1	15.8 (0.07)	0.083
2	16.0 (0.05)	0.083
3	17.9 (0.11)	0.083
4	18.6 (0.03)	0.083
5	14.3 (0.03)	0.083
6	13.7 (0.04)	0.083
7	16.1 (0.05)	0.083
8	17.7 (0.03)	0.083
9	16.1 (0.02)	0.166

[a] Average of three replicates. Values in parentheses are standard deviations.

Table 2. Mean RH, T, and EMC of the aeration air for all experiments.

Aeration Period, day	RH, %[a]	T, °C	EMC, %wb
1	46.3 (6.08)	23.9 (2.85)	11.0 (0.99)
2	49.3 (5.93)	22.8 (1.59)	11.4 (0.94)
3	49.7 (1.45)	22.2 (0.56)	11.5 (0.23)
4	49.4 (1.23)	22.3 (0.59)	11.5 (0.19)
5	51.0 (1.93)	16.8 (0.46)	12.0 (0.30)
6	51.6 (1.68)	16.6 (0.54)	12.1 (0.26)
7	68.8 (3.62)	11.3 (0.51)	15.1 (0.69)
8	71.1 (2.16)	11.0 (0.54)	15.5 (0.43)

[a] Values in parentheses are standard deviations.

At the end of each 3-h aeration period, the chamber T was set to the average grain T to minimize conductive heating or cooling until the next aeration period. Twenty hours after the previous aeration period, grain samples were collected from the top of each column to determine MC by oven-drying. These MCs were later compared to EMC values. Dry wheat contained in the 1.52-m columns was repeatedly used for experiments 1 to 9. To re-condition wheat to the initial MC for the next experiment, columns were aerated at a T and RH of 23.9°C and 50%, respectively, for 72 h.

Analysis of Data

Analysis of data involved descriptive analysis and comparison of trends. Measured CO_2 concentrations at various grain depths, i.e., 0 m (headspace), 0.76, 2.29, 3.81, 5.33, and 6.86 m (exhaust), during each aeration period were plotted against time. Because minimum and maximum CO_2 concentrations varied considerably day-to-day and between experiments, CO_2 concentrations were normalized using the maximum CO_2 measured for an aeration cycle. Experiments that had similar MC for the high-MC wheat were compared in terms of observed trends in CO_2 concentrations during aeration.

To determine the relationship among variables (e.g., CO_2, grain MC, grain T, and exhaust peak CO_2), multiple-regression analysis was done using SAS (Release 9.1, SAS Institute Inc., Cary, N.C.). A 5% level of significance was used to determine the significance of the relationships.

EMC of the wheat calculated from T and RH readings using the Chung-Pfost equation were compared with actual MCs (from the oven-drying method), using paired t-test and linear-regression analysis at a 5% significance level.

Results and Discussion

CO_2 Concentration

Figure 2 shows CO_2 concentration levels for Experiment 1 (15.8% high-MC wheat) during the first aeration period at 21.5°C aeration T. Only four curves are shown because the CO_2 sensor at the exhaust (6.86 m), and at 5.33 m had been damaged due to electrical problems. At the headspace (0 m) of the high-MC wheat, initial CO_2 concentration just prior to aeration was 8125 ppm. During aeration, the concentration decreased rapidly with time. For locations 0.76, 2.29, and 3.81 m, initial CO_2 concentrations were approximately 500 ppm; during aeration, the concentrations increased to a maximum value and then decreased rapidly with time. In addition, maximum

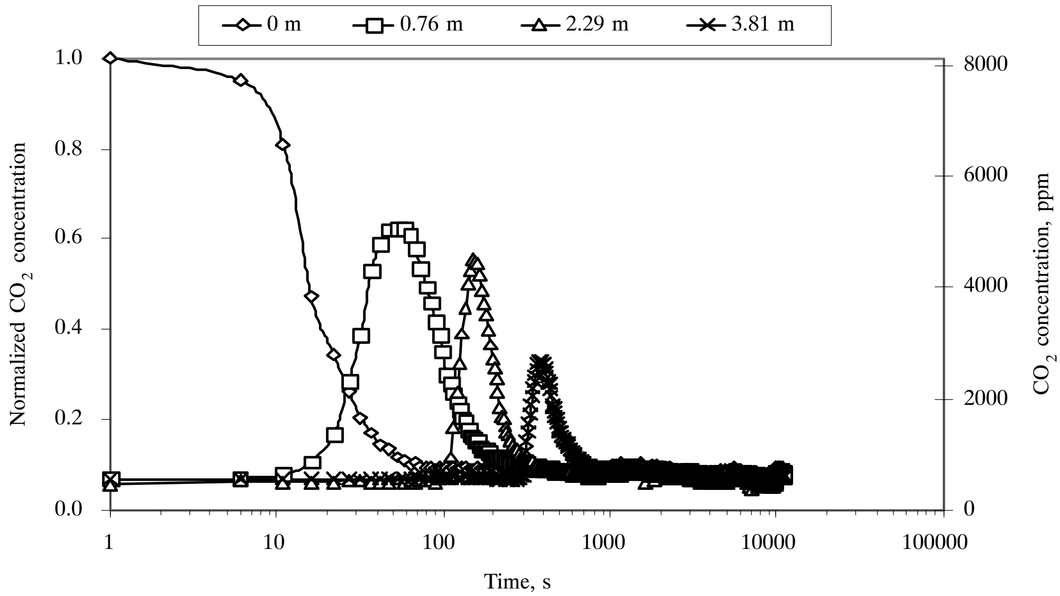

Figure 2. Measured CO_2 concentrations during the first 3-h aeration period for experiment 1. Wet grain MC =15.8 %, average grain temperature = 29.9°C, airflow = 0.083 m^3/min/tonne.

concentration decreased with distance from the high-MC wheat. Decreasing maximum concentrations were due to the dilution of CO_2 with aeration and interstitial grain air. At the end of the 3-h aeration period, CO_2 concentrations at the different locations were relatively uniform and reached a value of approximately 530 ppm, close to ambient atmospheric conditions.

Figure 3 shows CO_2 concentration levels during the last 3-h aeration period of Experiment 1. The peaks were considerably smaller (<1000 ppm), possibly due to grain cooling. With lower aeration T (15.2°C), CO_2 production could have been suppressed. CO_2 concentrations for aeration periods 2 to 7 of Experiment 1 had similar trends and were between the two extremes (aeration periods 1 and 8). However, CO_2 concentration at the exhaust (6.86-m location) did not show visible peaks for aeration periods 2 to 8 (days 2 to 8).

Experiment 7 used high-MC wheat at 16.1% MC_{wb} in the first column. Shown in figures 4 and 5 are CO_2 concentrations during aeration periods 1 and 8. For the first aeration period at 21.4°C aeration T, initial CO_2 concentrations were 3867 ppm at the headspace (0 m), 957 ppm at 0.76 m, 1162 ppm at 2.29, 1543 ppm at 3.81 m, 1338 ppm at 5.33 m, and 498 ppm at 6.86 m (exhaust). Initial CO_2 concentrations in the columns containing dry wheat had increased considerably (twice to thrice the ambient level) compared to Experiment 1, with Experiments 2 to 6 performed in between. Gonzales (2007) confirmed the reason

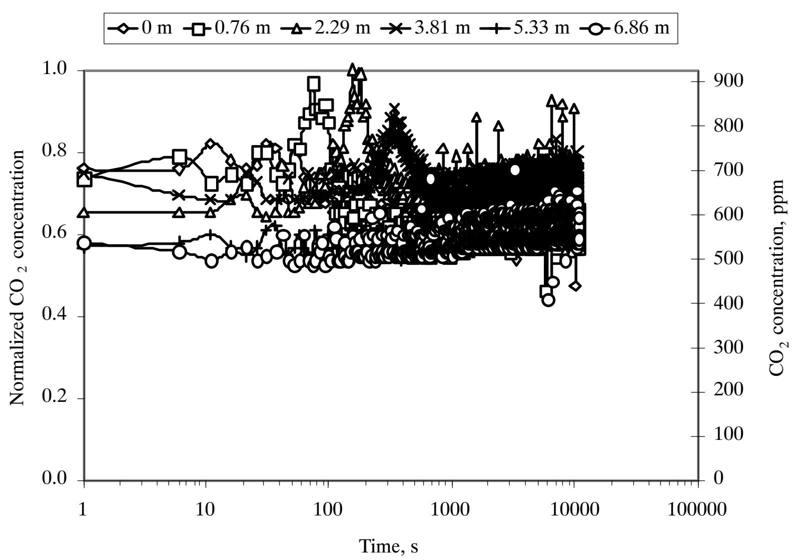

Figure 3. Measured CO_2 concentrations during the eighth 3-h aeration period for experiment 1. Wet grain MC =12.2%, average grain temperature = 15.9°C, airflow = 0.083 m^3/min/tonne.

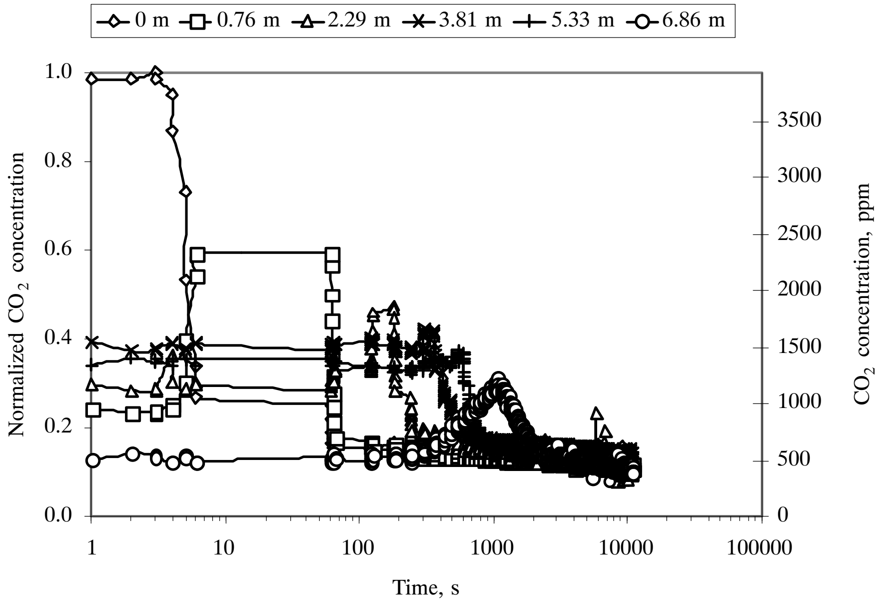

Figure 4. Measured CO_2 concentrations during the first 3-h aeration period for experiment 7. Wet grain MC =16.1%, average grain temperature = 29.4°C, airflow = 0.083 m^3/min/tonne.

for this was an increase in the mold colony population of the dry grain after repeated experimental aerations. During aeration 1, maximum CO_2 concentrations generally decreased with depth. As the grain cooled, CO_2 production was again suppressed resulting in smaller and almost indistinguishable CO_2 peaks on the successive aeration periods as illustrated by aeration 8 (10.4°C) concentrations (fig. 5).

Similar trends were observed for the 18% and 14% MC grain. Peaks were substantially larger for 18% MC grain than for the 14% MC grain, with the pre-aeration CO_2 concentration of the headspace (0 m) at >9999 ppm for 18% MC and <1500 ppm for 14% MC.

Experiments 3, 4, and 8 used high-MC wheat of approximately 18% MC_{wb}. Higher initial CO_2 concentrations at the headspace (0 m) were observed compared to the 16% high-MC wheat experiments. Also, compared to the 16% high-MC wheat, the CO_2 peaks were still distinguishable during the last aeration period (day 8). Experiments 5 and 6 of 14% high-MC wheat showed lower CO_2 concentrations at 0 m compared to 16% and 18% high-MC wheat.

Peaks of CO_2 concentration (normalized values) during the first, fourth, and eighth aeration periods of all experiments with nominal 16% MC_{wb}, high-MC wheat are plotted in figures 6 to 8. Experiments 1, 2, and 7 showed

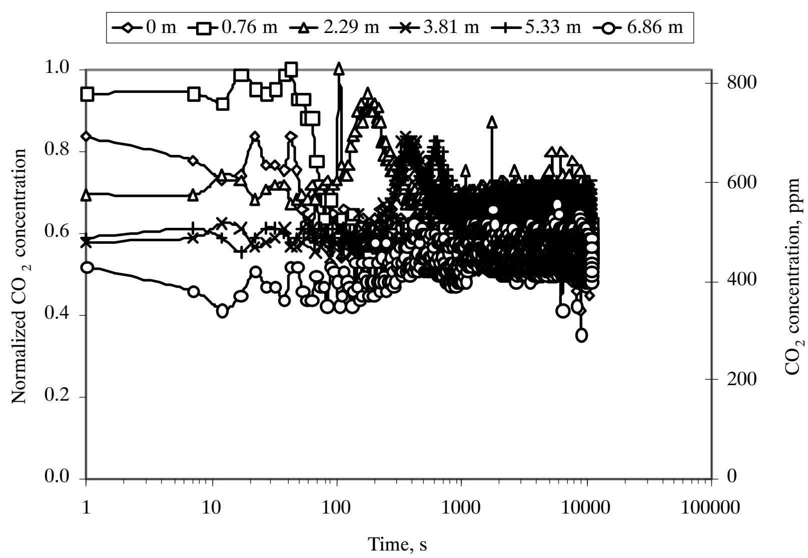

Figure 5. Measured CO_2 concentrations during the eighth 3-h aeration period for experiment 7. Wet grain MC = 13.2%, average grain temperature = 10.8°C, airflow = 0.083 m^3/min/tonne.

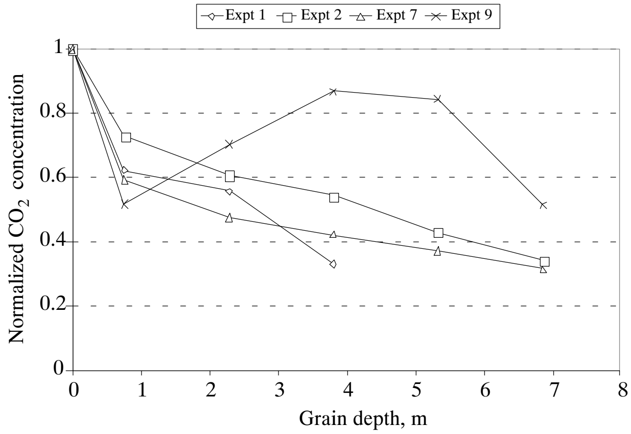

Figure 6. Normalized peak CO_2 concentrations during the first aeration period using 16% MC_{wb} high-MC wheat. Normalized CO_2 concentrations were obtained by dividing all data values by the maximum CO_2 concentration measured during aeration. Normalizing values were 8125, 2089, 3928, and 4785 ppm for Experiments 1, 2, 7, and 9, respectively.

similar trends with the highest CO_2 concentration in the high-MC wheat at the headspace during the first aeration period (fig. 6). Experiment 9 (16% MC_{wb} wheat aerated at higher airflow) showed higher CO_2 levels at locations 2.29 to 5.33 m. During the fourth aeration period (fig. 7), wheat aerated at the higher airflow rate still showed higher CO_2 peaks at locations 2.29 to 5.33 m. Peak CO_2 concentration in the eighth aeration period (fig. 8) did not change considerably between locations at lower aeration T; CO_2 values approached 500 to 600 ppm.

Figures 9 to 11 showed normalized peak CO_2 concentrations during the first, fourth, and eighth aeration periods of the three experiments with nominal 18% MC_{wb} wet wheat (Experiments 3, 4, and 8). The three experiments showed similar trends for the first aeration period (fig. 9); however, during the fourth (fig. 10) and eighth (fig. 11) aeration periods, Experiment 8 showed higher maximum CO_2 concentrations at locations 2.29 to 6.86 m. The higher

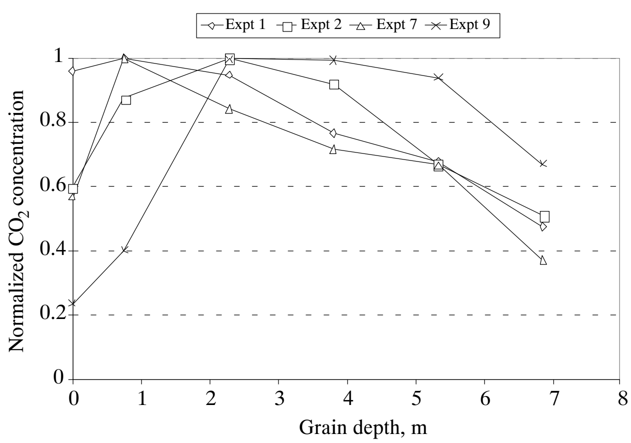

Figure 7. Normalized peak CO_2 concentrations during the fourth aeration period using 16% MC_{wb} high-MC wheat. Normalized CO_2 concentrations were obtained by dividing all data values by the maximum CO_2 concentration measured during aeration. Normalizing values were 1503, 1093, 2460, and 3154 ppm for Experiments 1, 2, 7, and 9, respectively.

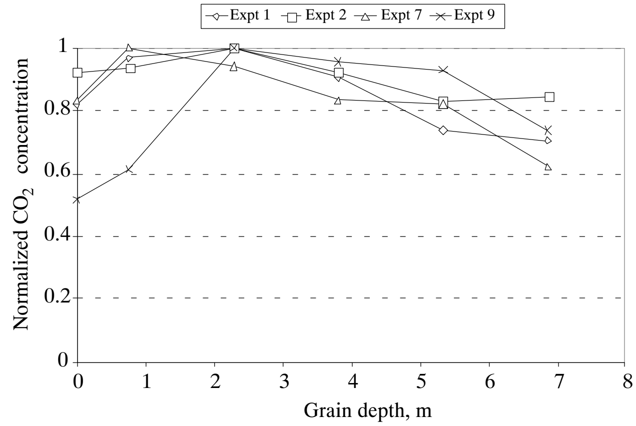

Figure 8. Normalized peak CO_2 concentrations during the eighth aeration period using 16% MC_{wb} high-MC wheat. Normalized CO_2 concentrations were obtained by dividing all data values by the maximum CO_2 concentration measured during aeration. Normalizing values were 927, 634, 830, and 1113 ppm for Experiments 1, 2, 7, and 9, respectively.

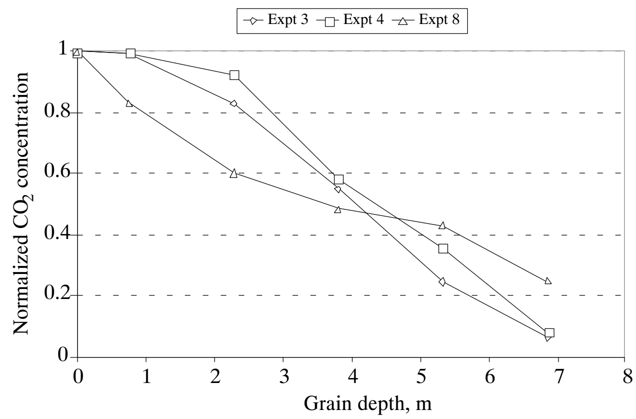

Figure 9. Normalized peak CO_2 concentrations during the first aeration period using 18% MC_{wb} high-MC wheat. Normalized CO_2 concentrations were obtained by dividing all data values by the maximum CO_2 concentration measured during aeration. Normalizing values were 9990, 9910, and 9990 ppm for Experiments 3, 4, and 8, respectively.

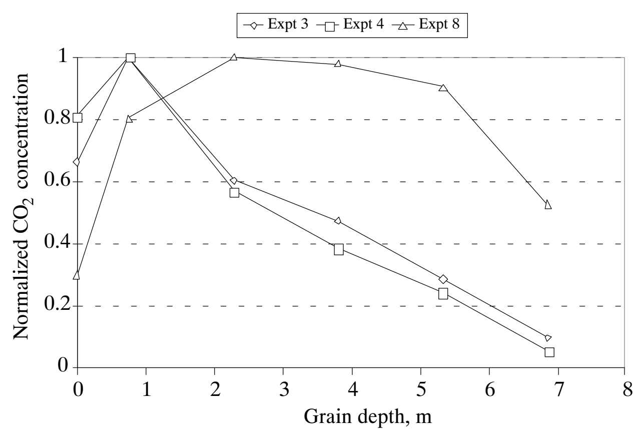

Figure 10. Normalized peak CO_2 concentrations during the fourth aeration period using 18% MC_{wb} high-MC wheat. Normalized CO_2 concentrations were obtained by dividing all data values by the maximum CO_2 concentration measured during aeration. Normalizing values were 5820, 9960, and 3935 ppm for Experiments 3, 4, and 8, respectively.

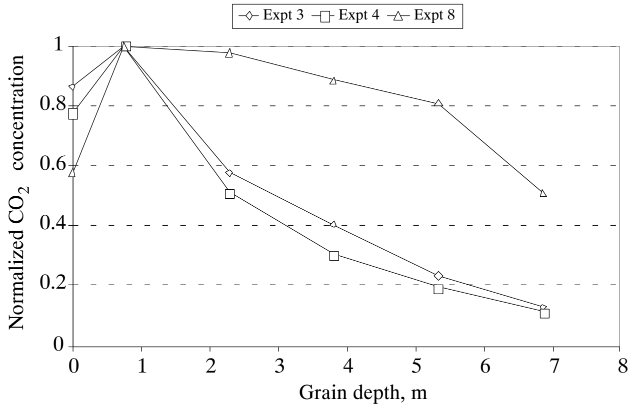

Figure 11. Normalized peak CO_2 concentrations during the eighth aeration period using 18% MC_{wb} high-MC wheat. Normalized CO_2 concentrations were obtained by dividing all data values by the maximum CO_2 concentration measured during aeration. Normalizing values were 3955, 6093, and 1738 ppm for Experiments 3, 4, and 8, respectively.

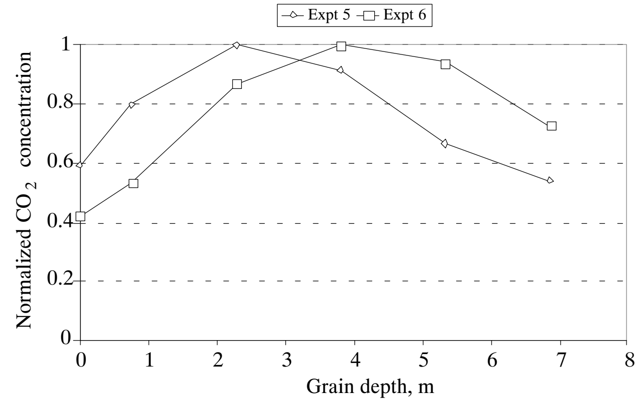

Figure 13. Normalized peak CO_2 concentrations during the fourth aeration period using 14% MC_{wb} high-MC wheat. Normalized CO_2 concentrations were obtained by dividing all data values by the maximum CO_2 concentration measured during aeration. Normalizing values were 1640 and 1650 ppm for Experiments 5 and 6, respectively.

normalized concentration for Experiment 8 could be due to actual higher initial CO_2 concentrations observed compared to Experiments 3 and 4.

Figures 12 to 14 showed normalized peak CO_2 concentrations measured during the first, fourth, and eighth aeration periods for Experiments 5 and 6. In the first aeration period (fig. 12), peak CO_2 concentration was highest at 2.29 m for Experiment 5 and at 0.76 m for Experiment 6. CO_2 concentration was the highest in both the fourth (fig. 13) and eighth (fig. 14) aeration periods of Experiment 6 at 3.81 m and Experiment 5 at 2.29 m. For all aeration periods, peak CO_2 concentration at 6.86 m was the lowest.

Relationship between Grain MC, Grain T, CO_2 Concentration, and Exhaust Peak CO_2

Regression analysis, using all experimental data, showed that the initial measured CO_2 concentration of the wet grain mass was weakly related to its MC and T ($p<0.05$). Also, the exhaust peak CO_2 concentration was poorly correlated to the CO_2 initial concentration and MC of the wet grain ($p<0.05$). These results suggest that CO_2 sensors were not very effective in detecting high-MC conditions using this generalized analysis method. It must be stated though that under many conditions there was a visually apparent relationship between the initial CO_2 and CO_2 peaks, with the MC of the high-moisture grain. Expected results were that high MC wheat would evolve large amounts of CO_2 , and conversely, low MC wheat would evolve relatively little CO_2 above ambient air CO_2. This was not observed consistently and the dry wheat increased evolution of CO_2 with repeated use. Mold analysis of the dry wheat samples are presented in detail by Gonzales (2007) and confirm mold colonies increased substantially during the progression of experimental use.

Equilibrium Moisture Content

A representative plot of the calculated initial EMC of the wheat and the EMC obtained 24 h after each aeration period at 0.083 m^3/min/tonne airflow rate, is shown in figure 15. Values were recorded under stable conditions and were the average measurements over 1-h prior to the next aeration period. Standard deviations of individual 1-h measurements ranged from 0.0003 to 0.018% MC. The wheat EMC at the

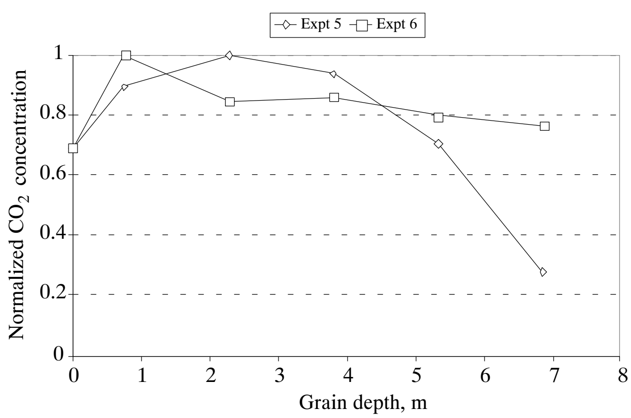

Figure 12. Normalized peak CO_2 concentrations during the first aeration period using 14% MC_{wb} high-MC wheat. Normalized CO_2 concentrations were obtained by dividing all data values by the maximum CO_2 concentration measured during aeration. Normalizing values were 2011 and 1201 ppm for Experiments 5 and 6, respectively.

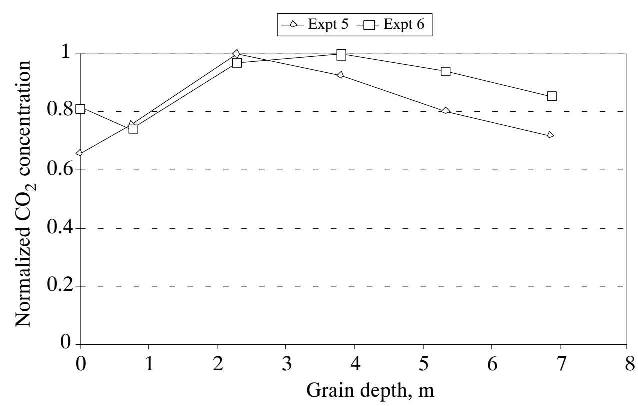

Figure 14. Normalized peak CO_2 concentrations during the eighth aeration period using 14% MC_{wb} high-MC wheat. Normalized CO_2 concentrations were obtained by dividing all data values by the maximum CO_2 concentration measured during aeration. Normalizing values were 800 and 683 ppm for Experiments 5 and 6, respectively.

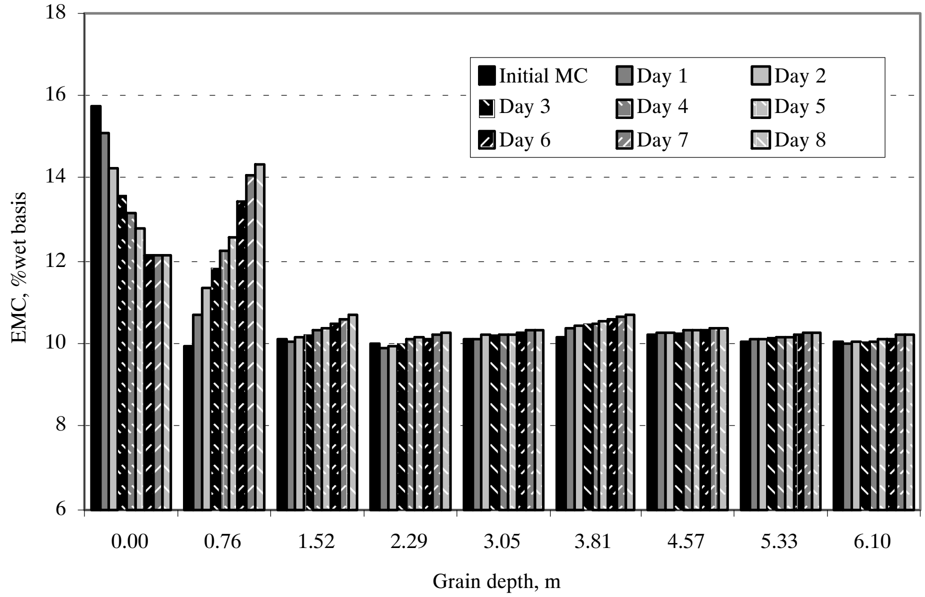

Figure 15. Calculated EMC_{wb} of the wheat at different locations for experiment 1 (15.8% MC_{wb}, 0.083 m^3/min/tonne airflow rate) 2 h before aeration.

headspace decreased from day 1 to day 6 and increased on days 7 and 8, because aeration air EMC was higher than grain EMC. It was not possible to lower aeration EMC due to environmental chamber/system constraints. Due to moisture transfer from the high-MC grain, EMC of the wheat at 0.76 m increased substantially. After each aeration period, grain had absorbed moisture at each sensor location from the aeration air and is shown by the slight increases in wheat EMC for depths 1.52 through 6.10 m. Other experiments at 0.083 m^3/min/tonne airflow rate showed very similar results. The same trend was also observed for Experiment 9 (fig. 16) at 0.166 m^3/min/tonne airflow rate, but the wheat at the headspace dried faster due to higher airflow.

Figure 17 compares oven-dried MC measurements after the aeration cycle was completed for each experiment and corresponding calculated EMC values. The regression equation shows a coefficient of determination (R^2) of 0.9, which indicates that the sensor readings (calculated EMCs) were linearly related to the MC results by the oven-drying method (measured MCs). Standard deviation of the difference between measured MC and calculated EMC values is 0.51. Results of the paired t-test showed that values

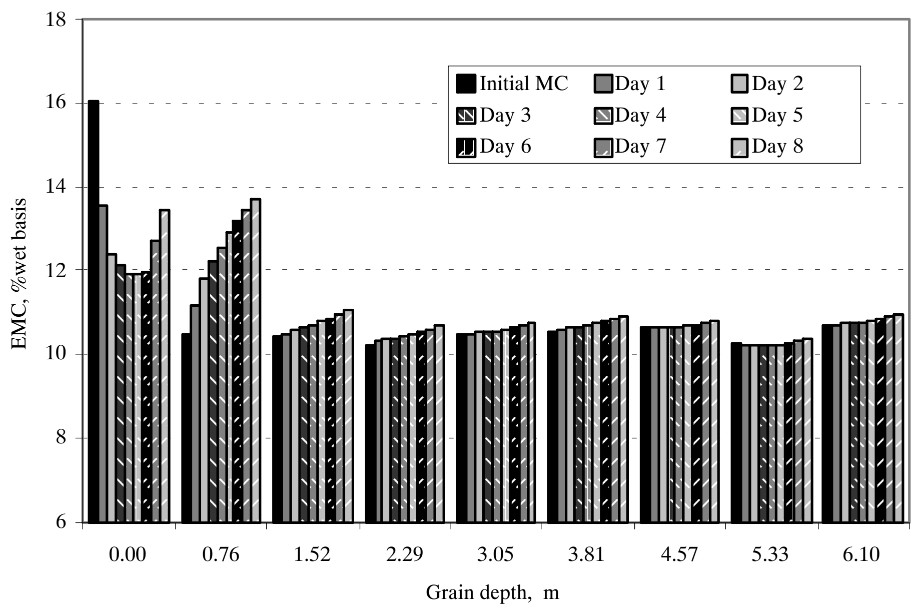

Figure 16. Calculated EMC_{wb} of the wheat at different locations for experiment 9 (16.1% MC_{wb}, 0.166 m^3/min/tonne airflow rate) 2 h before aeration.

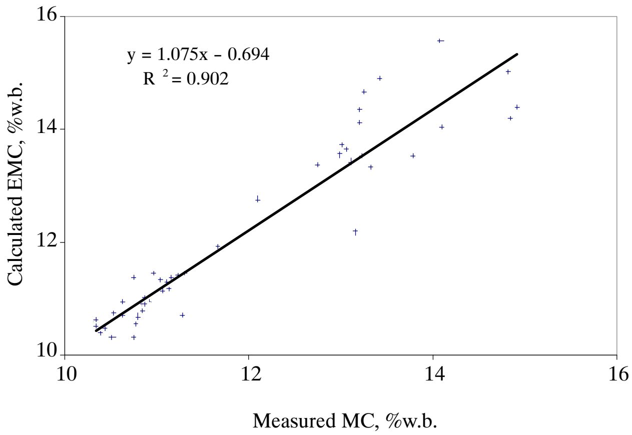

Figure 17. Regression line of the final wheat MC measurements obtained by oven-drying (measured MC) and EMC sensor (calculated EMC).

were not significantly different ($p>0.05$). The percent difference between calculated EMC and measured MC ranged from 0 to 11.1%. These results suggest that EMC sensors were effective in detecting moisture changes in grain but are not particularly accurate for moisture measurement. This is likely due to the inaccuracy of using a generalized EMC prediction equation and sensor error. Results also show that high grain moisture in the top affected grain MC throughout the bin and monitoring moisture at the bin top and bottom could be effective in detecting moist grain conditions.

Wheat Temperature

Table 5 shows average grain T after each aeration period for each experiment. As expected, T of the wheat decreased as aeration T decreased from the first to the eighth aeration period. In Experiment 1, aeration T for aeration periods 1 through 6 was set at approximately 21.1°C, while aeration T for periods 7 to 8 was set at 15.6°C. For Experiments 2 to 5 and 7 to 9, aeration T for periods 1 through 4 was set at 21.1°C, 15.6°C for periods 5 and 6, and 10°C for periods 7 and 8.

Conclusions

Research found the use of RH, T, and CO_2 sensors to improve storage monitoring of wheat by direct measurement of EMC and the detection high levels of CO_2 attributed to a localized wet grain mass, during aeration. CO_2 sensors were effective in detecting moist grain conditions during aeration by examining peak CO_2 measurements when grain T was high but were less effective as grain T lowered as a result of aeration. As such, grain T needs to be considered when interpreting CO_2 levels and the grain condition. Based on the test conditions used, monitoring CO_2 levels at the exhaust during downdraft aeration would be largely adequate in determining adverse storage conditions and would be equivalent to monitoring at the aeration duct in actual facilities. While CO_2 peaks in all experiments were lowest at this location because of dilution, a high concentration was still detected due to the high moisture grain. The EMC sensors detected moisture changes in dry grain due to the moisture front movement from high-MC grain. Interpretation of data was straightforward but required sensors placed throughout the grain mass. Sensors close to the high-MC grain readily indicated this condition. The increasing levels of CO_2 within the dry grain mass after repeated experiments and aeration cycles indicated EMC sensors may not always indicate the storability of the grain. As such, the CO_2 measurements may more readily indicate storability. Future research should quantify or control the condition of the experimental wheat in regard to microflora activity. An approach of measuring peak CO_2 concentrations coupled with measuring total CO_2 evolved per unit grain mass per unit time period, during aeration, may provide better information of grain condition.

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Table 5. Average grain temperature[a], C, after each aeration period.

	Expt 1	Expt 2	Expt 3	Expt 4	Expt 5	Expt 6	Expt 7	Expt 8	Expt 9[b]
Initial T	29.9	30.1	30.1	29.7	29.5	29.2	29.6	29.9	29.8
Aeration Period									
1	25.2	25.2	24.9	25.2	25.8	29.7	25.3	26.0	25.9
2	23.2	23.4	23.0	23.3	23.7	26.0	23.8	24.3	23.6
3	22.2	22.2	22.0	22.4	22.8	23.7	22.9	23.2	22.6
4	21.9	21.7	21.9	22.1	22.1	22.4	22.3	22.6	22.2
5	21.8	18.0	18.2	18.8	19.1	18.8	19.0	19.4	18.8
6	21.2	16.1	17.0	17.0	17.3	16.7	17.1	17.6	16.7
7	16.9	12.2	13.1	13.2	13.6	12.5	13.2	13.8	12.9
8	15.9	10.5	11.5	11.1	11.4	10.8	10.8	11.7	10.7

[a] Average of nine sensor readings.
[b] Experiment at higher airflow rate.

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